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Effect of Slow Sand Filter Maintenance on Water Quality

Syracuse Univ., NY

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JOURNAL ARTICLE

The Effect of Slow Sand Filter Maintenance on Water Quality

Thomas R. Cullen and Raymond D. Letterman

Full-scale municipal slow sand filters at seven sites in the Syracuse, N.Y., area were monitored before, during, and after filter scraping to verify the presence or absence of a ripening period, to determine the filter run length, and to quantify the labor and material required for scraping and resanding operations. Results showed some evidence of a ripening period, ranging from 6 h to 2 weeks, in four of the 10 operations monitored. The presence or absence of a ripening period did not seem to be related to the use of prechlorination, to water temperature, to scraping methodology, or to frequency of filter maintenance. The factor that seemed to have the most significant effect on the quality of the filtrate was the amount and nature of the particulate matter present in the raw water.

During the operation of a slow sand filter, a layer of filtered particulate matter and biological growth forms at the top of the sand bed. The buildup of this layer during a filter run increases the head loss across the filter over time until a limiting head loss is reached and the top layer must be removed—an operation known as scraping. Because the scraping operation decreases the amount of sand in the filter bed, the bed must eventually be replenished with clean sand—an operation called resanding. In most small slow sand filter installations, scraping and resanding are labor-intensive operations and, in terms of cost, the major maintenance requirement.

Maintenance of slow sand filters may be followed by a ripening period. A ripening period is the time immediately after a scraped or resanded filter is put back into operation during which the effluent quality is significantly poorer than that for a filter that has been on-line in an undisturbed state for a significant period of time, e.g., several weeks.

The literature contains evidence that the processes of scraping and resanding result in ripening periods in full-scale slow sand filters[1-3] and in some pilot-plant filters.[4] However, the results of recent research have not shown a ripening period.[5,6] Evidence exists that supports the contention that resanding of a filter bed has a more detrimental effect on effluent quality than scraping.[7]

The results described in this article were obtained in a study conducted from spring 1983 to fall 1984. Full-size municipal slow sand filters were monitored before, during, and after filter scraping and resanding. The study had the following objectives:

1) verify the presence or absence of a ripening period by measuring the filtered water quality before and after filter scraping or resanding and comparing this quality to that of a control filter and the raw water;

2) determine the filter run length (time

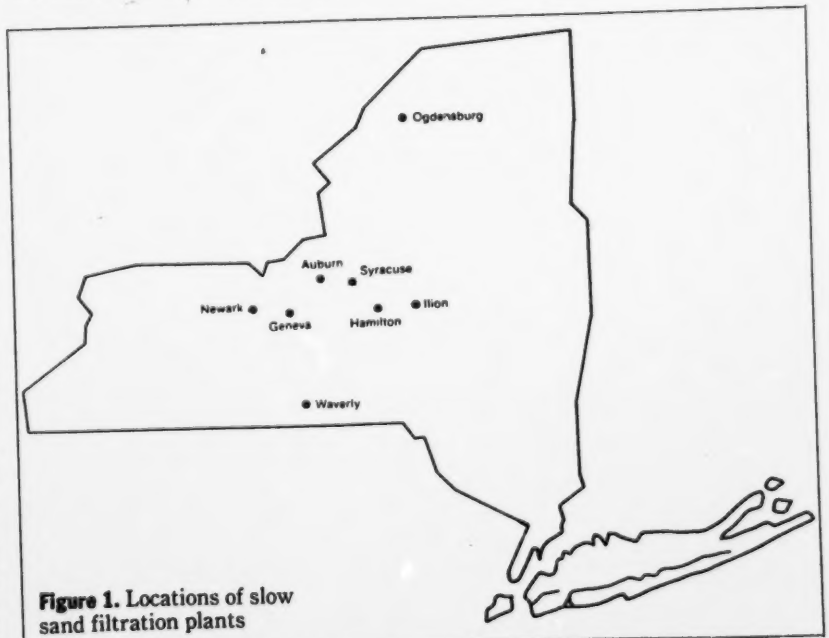

Figure 1. Locations of slow sand filtration plants

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between scraping operations) and relate this information to relevant design and operations parameters, such as filtration rate and raw water quality; and

3) quantify the labor and material required for the scraping and resanding operations and determine the cost of this maintenance in dollars per volume of water treated.

Background

Slow sand filters have been used to treat drinking water since 1826, when James Simpson constructed a plant to treat water for the Chelsea Water Company in London. Although some information is available, much of the work on slow sand filtration in the United States was done in the late 1800s and early 1900s before rapid sand filtration became almost universally popular. Recent research has used analytical techniques that were not available in 1900 or that have been modified since then.

Scraping is generally thought to result in a deterioration of filter effluent quality immediately after resumption of operation. The duration of the water quality improvement or filter ripening period is variable, but it can last as long as several days. Higher concentrations of plate count bacteria (two to six times the monthly average) were observed for 1 to 2 days after scraping in a slow sand filter pilot-plant study conducted in Pittsburgh in 1898.[8] (The 48 postscraping data points were excluded when the monthly average was computed.) This sort of result is suggested by Huisman and Wood,[9] but they did not present data to show the extent of quality deterioration that might occur.

In *The Filtration of Public Water Supplies*,[2] Hazen stated that Piefke in Germany had suggested wasting filtered water for one day after scraping and for a full week after filter sand had been replaced. Hazen reported that the Imperial Board of Health rules required that German filters be constructed so that filtered water could be wasted. Hazen also reported that experiments in Germany and at the Lawrence Experiment Station in the United States had shown higher bacterial counts in filtered water for one or more days after scraping. The increase in the bacterial count was greater when the sand filter depth was reduced and when the rate of filtration was higher.

Results of recent slow sand filter research have not shown the detrimental effects of scraping on effluent quality. Research by the US Environmental Protection Agency (USEPA), published by Logsdon and Lippy,[10] indicate no deterioration of water quality during two different runs when a filter was restarted after scraping. This is in contrast to the 6-week interval of poor effluent quality observed when the filter

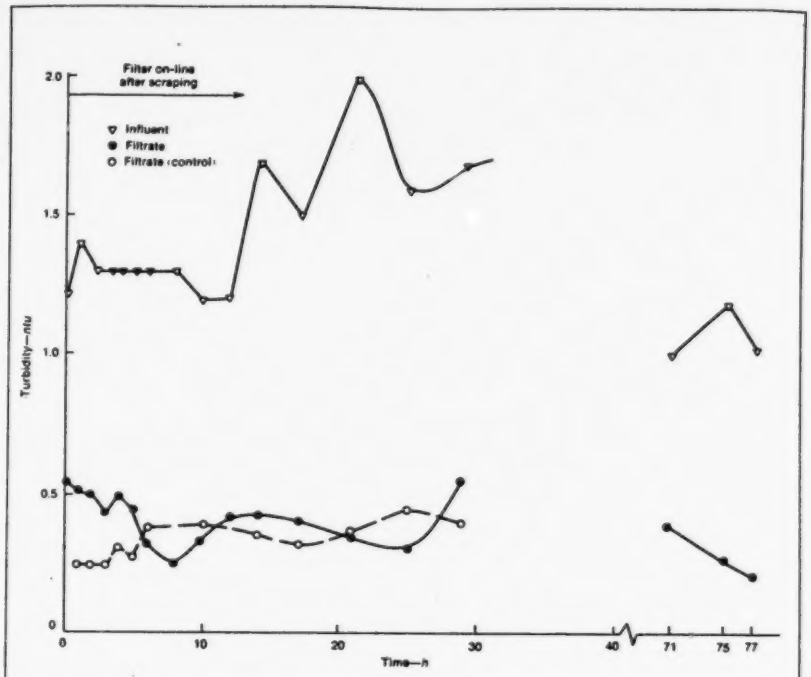

Figure 2. Turbidity versus time at Auburn (July 1983; filter 1)

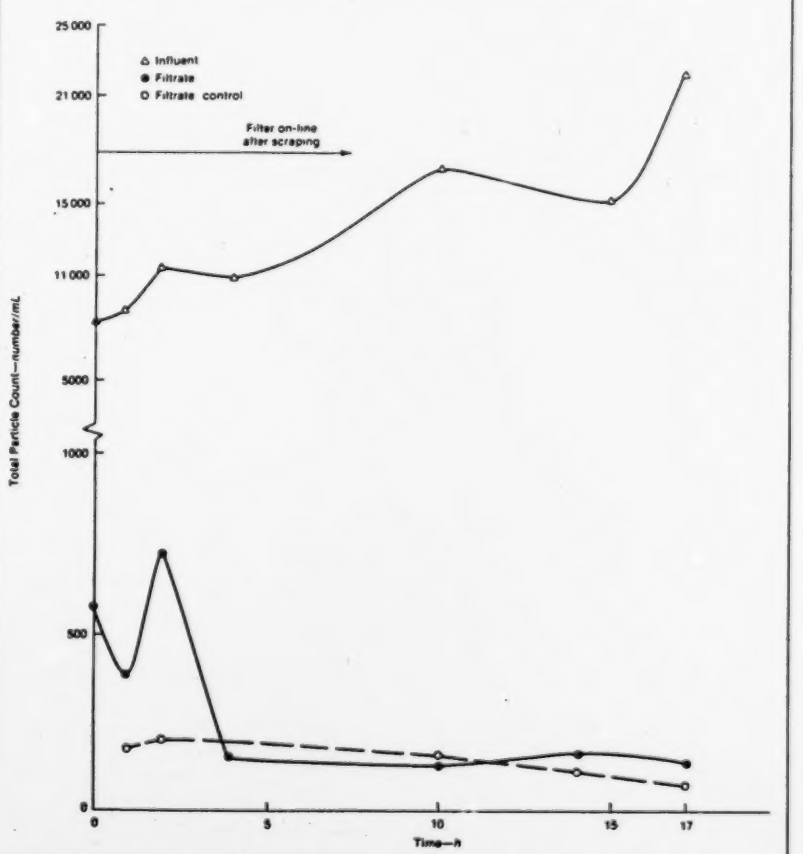

Figure 3. Particle count versus time at Auburn (July 1983; filter 1)

TABLE 1

Characteristics of the slow sand filtration plants visited during the study

Location	Average Operating Flow Rate		Raw Water Source	Average Raw Water Turbidity (from plant records)	Total Slow Sand Filter Area		Average Operating Filtration Rate		Prechlorination	Covered Filters
	mgd	*ML/d*		*ntu*	*sq ft*	*m²*	*fph*	*m/h*		
Auburn	6.0	22.7	Owasco Lake	1.5–2.0	74 100	6883	0.45	0.14	No	Yes
Geneva	2.5	9.4	Seneca Lake	1.0	30 492	2832	0.62	0.19	No	Yes
Hamilton	~0.3	~1.1	Woodman's Pond	1.0–1.5	12 724	1182	0.13	0.04	No	No
Ilion	1.5	5.6	Several small streams feeding reservoir	3.0	19 526	1813	0.52–0.59	0.16–0.18	Yes	2 uncovered, 3 covered, 1 not used
Newark	2.0	7.5	Canandaigua Lake	3.0 (summer) 1.0 (winter)	21 684	2014	0.52	0.16	Yes	Yes
Ogdensburg	3.6	13.6	St. Lawrence River	1.0–1.4	33 600	3121	0.59	0.18	No	Yes
Waverly	1.2	4.5	Surface runoff to reservoirs	7.0–9.0 (may be as high as 20–40 during high runoff periods)	12 000	1114	0.52	0.16	Yes	Yes

TABLE 2

Summary of filter ripening data

Location	Type of Operation	Date of Site Visit	Raw Water Turbidity *ntu*	Water Temperature		Filtrate Turbidity Approximately 5 h After Filter Startup—*ntu*		Evidence of Ripening Period	Approximate Length of Ripening Period *days*
				°F	*°C*	Scraped or Resanded Filter	Control Filter*		
Auburn	Scraping	July 1983	1.2–2.0	~66	~19	0.43	0.27	Yes	0.25
Auburn	Scraping	July 1983	1.2–2.0	~66	~19	0.28	0.27	No	
Auburn	Scraping	July 1984	2.0–2.8	~64	~18	0.22	0.23	No	
Geneva	Scraping	July 1983							
Hamilton	Scraping	May 1984	1.0–1.5	~53	~12	0.28	None	No	
Ilion	Scraping	July 1983	2.0–4.0	~73	~23	0.30	0.40	Minimal (particle count only)	0.5
Newark	Scraping	Aug. 1983	1.2–3.5	~55	~13	0.35	0.35	No	
Newark	Resanding	Jan. 1984	0.6–2.7	~39	~4	0.41	0.12	Yes	2
Ogdensburg	Scraping and resanding	Aug. 1983	0.3–0.6	~59	~15	0.12	0.10	No	
Ogdensburg	Scraping and resanding	Feb. 1984	1.0–1.2	~35	~2	0.22	0.24	No	
Waverly	Scraping	June 1984	6.0–11.0	~59	~15	2.3	1.6	Yes	10

*Filter on-line at least one month, except Ogdensburg where the filter was on-line one week

TABLE 3

Summary of filter scraping data

Location	Average Water Production per Filter Run		Average Frequency of Filter Scraping Operations	Amount of Sand Removed		Methods Used to Remove Sand	Workhours Required	
	gal/sq ft	*m³/m²*	*number per year*	*in.*	*mm*		per 1000 sq ft	per 100 m²
Auburn	6 844	278	4.3*	0.5	12	Shovels, hydraulic system	4	4
Geneva	15 718	640	2.0	1.0	25	Shovels, motorized buggy	4–5	4–5
Hamilton	4 302	175	2.0	1.0	25	Shovels, 50-gal (189-L) drums, backhoe	8–9	9–10
Ilion	15 487	630	1.8	3–4	75–100	Shovels, hydraulic system	23–42	25–45
Newark	10 122	412	3.3	1.0	25	Shovels, motorized buggy	2	2
Ogdensburg	2 978	121	12.0	1.0	25	Shovels, hydraulic system	4–5	4–5
Waverly	3 200†	130	9.7†	1.0	25	Shovels, wheelbarrows	5	5

*At Auburn, two scraping operations per year were actually occasions when the filters were raked and no sand was removed.
†Water production and scraping frequency were estimated for the future by Waverly personnel using data from a nine-month operations study. Waverly has had runs as short as two days.

TABLE 4

*Estimated operation and maintenance costs for slow sand filters**

Location	Average Operational Flow		Labor for Scraping	Labor for Resanding	Day-to-Day Activities	Total Labor Costs	Cost of Replacing Sand	Total Operation and Maintenance Unit Cost	
	mgd	*ML/d*	*workhours/year*	*workhours/year*	*workhours/year*	*$/year*	*$/year†*	*$/1000 gal*	*$/10 m³*
Auburn	6.0	22.7	1007	618	365	10 597		0.005	0.013
Geneva	2.5	9.4	374	218	365	9 570	3019	0.011	0.029
Hamilton	0.3	1.1	224		365	5 890	1260	0.065	0.17
Ilion	1.5	5.6	905	563	365	18 331		0.033	0.087
Newark	2.0	7.5	143	226	365	7 640	3586	0.016	0.042
Ogdensburg	3.6	13.6	8736	‡	365	23 811		0.020	0.052
Waverly	1.2	4.5	582	420	365	13 670	5772	0.053	0.14

*All cost figures are based on a $10/h wage rate, except at Auburn where $3/h was used because the workers are usually students.
†Sand costs based on typical value of $12/ton
‡Ogdensburg scrapes and resands simultaneously.

operation was first started and water was passed through new, clean sand. Also, pilot slow sand filters operated at Colorado State University did not show quality deterioration after scraping.[5]

One possible reason for the differences between results could be the size of the facilities and the extent to which filters have been disturbed during scraping and cleaning. Decades ago, the municipal filters were so large that maintenance personnel could not remove the sand without walking on the filters. Even the Pittsburgh pilot filters studied by Hazen were large enough (11 × 23 ft [3.3 × 7.0 m]) that the sand would have been disturbed during cleaning. In contrast to the large filters on which the observations of deteriorated water quality are based, the pilot-scale slow sand filters currently under study are generally very small. The USEPA Water Engineering Research Laboratory filter[11] is 1.5 × 1.5 ft (0.45 × 0.45 m), and other filters are from 1 to 2.5 ft (0.3 to 0.7 m) in diameter. The absence of walking and its resulting disturbances to the sand bed may be a factor in the high quality of water observed within the first day of renewed operation of the pilot slow sand filters.

During routine operation, slow sand filters do not require much labor on a daily basis. In less than an hour, many operators are able to monitor filter flow rate versus water consumption and adjust the rate if needed, obtain a filtered water turbidity sample and analyze it, check the chlorine residual and adjust it if necessary, monitor head loss, and record the appropriate operating data.

When a slow sand filter is removed from service for cleaning, the labor needs rise dramatically. One or more people may have to work for a portion of a day or longer to clean the filter. The amount of labor required is apparently related to working conditions, filter access (closed versus open filters), extent to which sand removal is mechanized, size of the filter, depth of sand removed in the scraping process, and extent of cleaning performed on filter walls. Resanding would be expected to take considerably longer than simply removing 0.75–1.5 in. (2–4 cm) of dirty sand from the top of the filter bed. If the water utility reuses sand previously removed from the filter during cleaning, sand washing may also involve extra labor.

Data that can be used to relate slow sand filter maintenance costs to filter size are limited, even though cleaning costs could exceed monitoring costs if the area of the filter is sufficiently large. Up-to-date information is needed so that the cost of operating and maintaining slow sand filters of various sizes can be estimated by engineers when conceptual designs are prepared and process options are considered.

Study methods

Seven slow sand filtration plants were chosen for study because of their proximity to Syracuse University, Syracuse, N.Y.—Auburn, Geneva, Hamilton, Ilion, Newark, Ogdensburg, and Waverly, N.Y. (Figure 1).

The typical study visit involved traveling to the plant site one or two days before a filter was to be scraped. The plant was toured and the plant records were examined to determine the filter run lengths and historical water quality. The workforce, techniques, and equipment used in scraping (or resanding) were determined by observations and interviews and were recorded. Samples were taken before and after scraping or resanding. The raw water and a control filter were also monitored during this period. (The control filter was a filter that had been continuously operated for a period of at least one month.)

Water quality parameters tested included turbidity, standard plate count bacteria, total coliform bacteria, and particle count. The filter bed sand was analyzed by performing a sieve analysis and a sand dissolution test. All sampling techniques and analytical methods were conducted in accordance with *Standard Methods*,[12] the *HIAC Particle Size Analyzer Instruction Manual*,[13] and the US Army's *Laboratory and Soils Testing Manual*.[14] Particle count measurements were made using a particle size analyzer.* Only particles with effective diameters in the range 2–60 μm were counted.

The average operating flow rates of the plants visited range from 0.3 mgd (1.1 ML/d) in Hamilton to 6.0 mgd (22.7 ML/d) in Auburn (Table 1). The raw water sources are primarily lakes and upland reservoirs, with the exception of Ogdensburg where the St. Lawrence River is used as a raw water source. The average raw water turbidity is below 3.0 ntu for all sites except Waverly where the turbidity may be as high as 40 ntu during periods of high runoff.

The areas of the slow sand filters at the plants visited range from 12 000 sq ft (1120 m²) at Waverly to 74 100 sq ft (6820 m²) at Auburn. The operating filtration rates are generally in the 3.4–4.6-gph/sq ft (0.14–0.19-m³/m²/h) range, with the exception of Hamilton, which operates at 1.0 gph/sq ft (0.04 m³/m²/h).

Three of the seven slow sand plants visited practice prechlorination. Newark prechlorinates to prevent algae from affecting the 8-mi- (12.8-km-) long transmission line that connects Canandaigua Lake with the filtration plant. Waverly practices prechlorination to oxidize iron and manganese in the influent. The purpose of prechlorination at Ilion was not determined. Prechlorination dosages are: Newark, 1 mg Cl_2/L; Waverly, 5 mg Cl_2/L; and Ilion, 12 mg Cl_2/L (summer), 4 mg Cl_2/L (winter). None of the plants measured the chlorine residual before or immediately after filtration.

All of the plants visited have covered filters, with the exception of Hamilton. Ilion has six filters: four covered (one of these is not presently used) and two open filters.

Results and discussion

Ripening period. In four of the ten maintenance operations (scraping and resanding) monitored during this study, there was some evidence of a ripening

*HIAC Model PC-320, Pacific Scientific Co., Montclair, Calif.

period. According to Figures 2 and 3, in which a ripening period is apparent, the filtrate turbidities and particle counts were greater for the recently scraped or resanded filter than for the control filter.

Typical turbidity and particle count data for maintenance operations that appeared to result in no ripening period are plotted in Figures 4 and 5. Turbidity and particle count values for the recently cleaned filter were similar to those for the control filter throughout the 48-h monitoring period.

In most cases, results for total plate count and total coliform bacteria showed no ripening period. Data for total plate count were, in general, scattered, while measurable coliform densities were found in less than 12 percent of the samples taken during the study. When coliforms were measurable, the removal efficiency was 95.7–99.7 percent, with 98–99-percent removal being typical.

The ripening period shown in Figures 2 and 3 lasted for approximately 6 h (0.25 days). (The details are summarized in the first line of Table 2.) During this time, effluent turbidity and particle count readings were approximately double those of the control. However, effluent turbidity was always <1.0 ntu.

A minimal ripening period, suggested by particle count data only, was observed after scraping at Ilion. During this time (0.5 days), the particle counts were occasionally double those of the control filter. However, turbidity readings were at or below control levels at all times.

Turbidity and particle count data showed evidence of a ripening period after a winter resanding operation at Newark. Turbidity measurements were approximately two to three times the control filter values, and the ripening period lasted 2 days. The length of this ripening period is most likely due to the nature of the resanding process, which involved draining of the sand bed and people working on the surface for a one-week period. It is possible that the long drainage time adversely affected the microorganisms within the bed and led to a deterioration in water quality.[9]

The 10-day ripening period indicated by turbidity data only, shown in Table 2, is a special case (Figure 6). Particle count data for the scraped filter were essentially equal to those of the control after 26 h of operation (Figure 7).

In the log-log plot of turbidity versus particle concentration (Figure 8), the results obtained for the samples collected at Auburn, Hamilton, Newark, and Ilion appear to cluster between the same trend lines. The data collected at Waverly plot significantly above the points that correspond to the other sites. For example, at Auburn, Hamilton, Newark, and Ilion, a particle concentration of 1000/mL corresponded to turbidity values in the range of 0.3 to 0.7 ntu. At Waverly, a

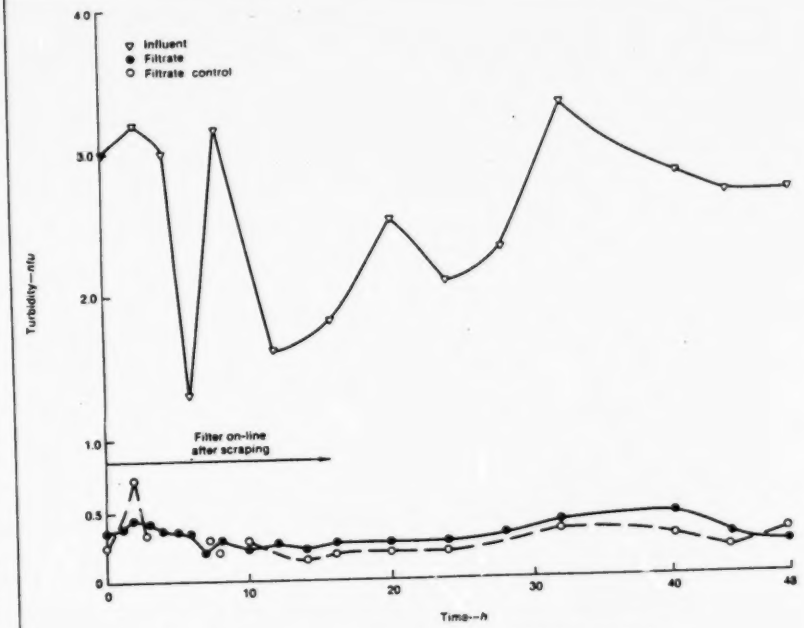

Figure 4. Turbidity versus time at Newark (August 1983; filter 1)

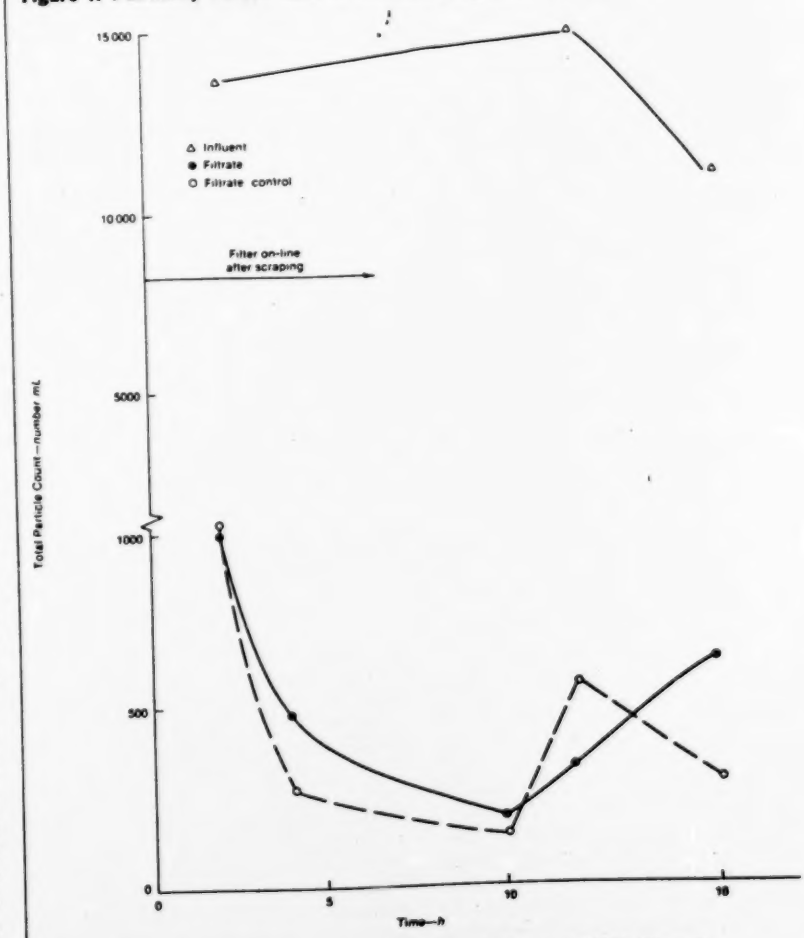

Figure 5. Particle count versus time at Newark (August 1983; filter 1)

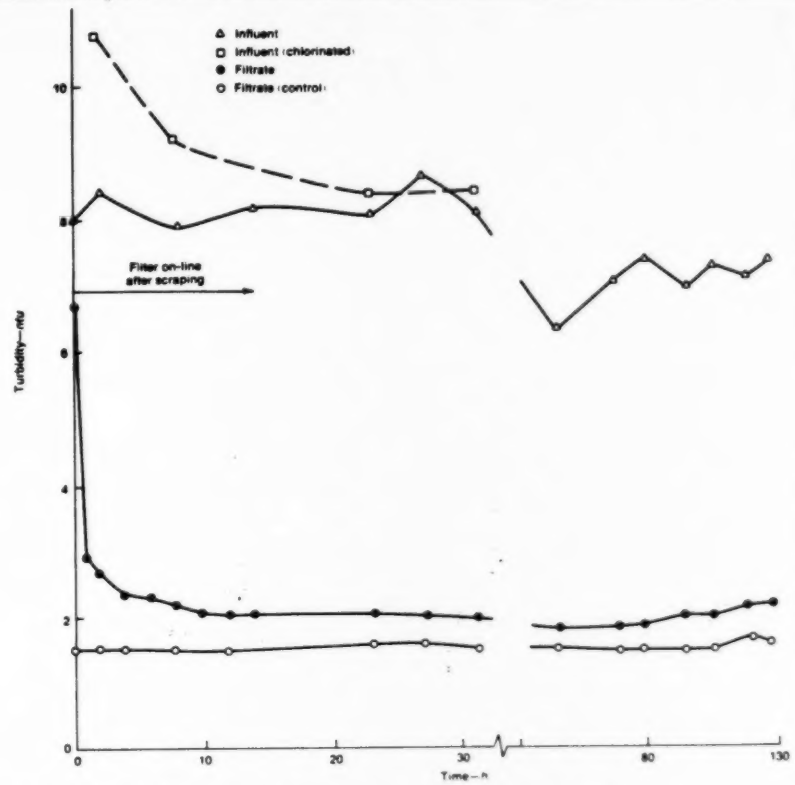

Figure 6. Turbidity versus time at Waverly (June 1984; filter 2)

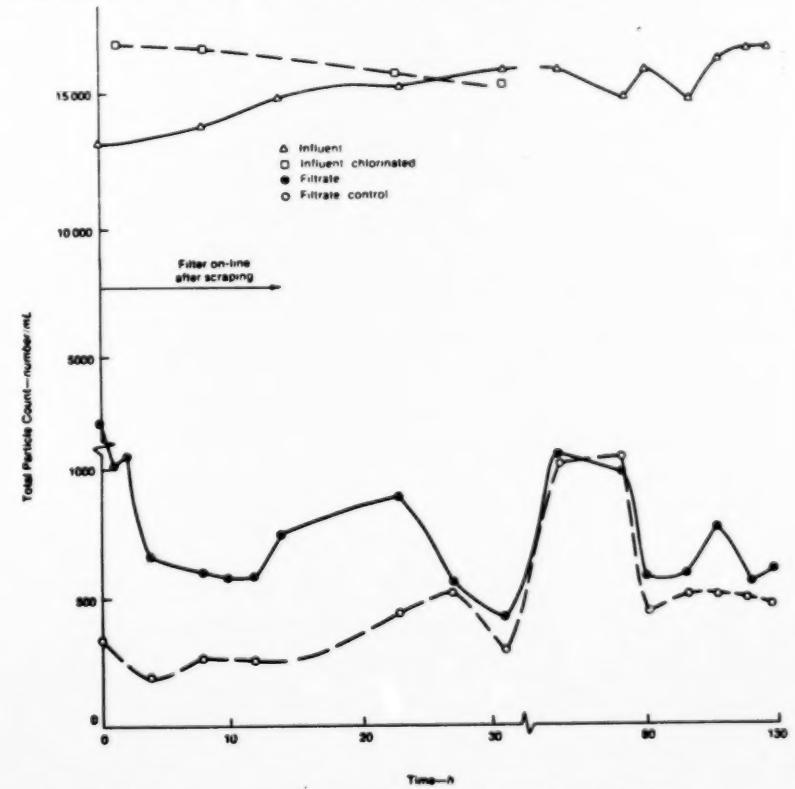

Figure 7. Particle count versus time at Waverly (June 1984; filter 2)

particle concentration of 1000/mL corresponded to turbidity values in the range of 1.8 to 3.0 ntu.

The results plotted in Figure 8 suggest that in terms of the removal of particles >2 μm in diameter, the filters at Waverly were as efficient (or more so) than the filters at other sites. Apparently, particles smaller than 2 μm passed through the filters at Waverly and had a significant effect on turbidity. Howard has noted that without pretreatment of the water, slow sand filters are unable to remove very fine turbidity.[15]

The results suggest that in some cases a recently scraped filter is less efficient than a ripened control filter in attenuating a spike input of lower quality raw water. This is evident in the semilog plot of the plate count data for Auburn (Figure 9). Approximately 16 h after startup, the raw water plate count began to increase and then peaked at about 1100 colonies/mL (from a usual level of 25-50 colonies/mL). Two hours later the recently scraped filter abruptly increased from control levels (2 colonies/mL) to 900 colonies/mL. But the control filter effectively attenuated this spike input; the maximum was 50 colonies/mL.

In this study the amount and nature of the particulate matter in the raw water seemed to be the most significant factor in determining filtrate quality. The presence or length of a ripening period did not seem to be related to scraping methods, frequency of maintenance, water temperature, or prechlorination.

Significance of prechlorination. It is usually assumed that the efficiency of filtration by a slow sand filter is determined, at least in part, by the presence of viable microorganisms within the filter bed and that, therefore, prechlorination in these systems would be detrimental to filter performance. The volume-weighted average turbidity of the effluent of the control filter was compared with that of the influent at each site and for each monitoring period during which a control filter was sampled. The values were averaged for the entire length of each sampling period and were used to calculate the percent turbidity remaining in the effluent.

The average and standard deviation of the values of the percent turbidity remaining for the three cases in which prechlorination was used (four sets of data) are 17 and 7.9 percent, respectively. For the three cases (six sets of data) in which there was no prechlorination, the average and standard deviation of the values of the percent turbidity remaining are 21 and 7.6 percent, respectively.

Although other factors may have obscured the true significance of adding chlorine before slow sand filtration, these results do not give a clear indication that prechlorination is detrimental to performance. In fact, in the plants sampled,

it may have had a slightly positive effect on turbidity removal.

Frequency of scraping. According to Table 3, the average water production per filter run ranged from 2980 gal/sq ft (121 m^3/m^2) at Ogdensburg to 15 720 gal/sq ft (640 m^3/m^2) at Geneva. The average frequency of filter scraping ranged from approximately two per year at Geneva, Hamilton, and Ilion to twelve per year at Ogdensburg. The unusually large number of scraping operations at Ogdensburg may be due to the method of maintaining the filters, during which the scraped-off sand is washed immediately and returned to the bed. Although this is an unusual practice, it results in the bed depth remaining constant. Since only the top layer of sand is ever removed and washed, deposited particulate matter and biological growth may eventually clog the lower layers of the bed.[16,17]

At Auburn each filter is scraped an average of 4.3 times per year. Two of these "scraping" operations, however, are actually occasions when the filter beds are raked and sand is not removed. Auburn plant personnel claim that raking breaks up the top layer of sand, reduces the head loss, and does not lead to any adverse effects on water quality. There is evidence in the literature that caution should be exercised with this method: raking of filter beds may lead to a sharp decline in effluent quality.[9]

The average water production and filter scraping frequency for Waverly—3200 gal/sq ft (130 m^3/m^2) and 9.7 times per year, respectively (Table 3)—are estimates for the future derived from an analysis by plant personnel of data from a nine-month operations study. In the past, Waverly has had filter runs as short as two days. Waverly is required by the New York State Health Department's Bureau of Public Water Supply to take its slow sand filtration plant off-line when one or more of the following three conditions are present in the raw water: turbidity >12.5 ntu; total iron >3.0 mg Fe/L; and manganese >1.0 mg Mn/L. When the slow sand plant is off-line, Waverly must rely exclusively on well water supplies.

Except for Waverly, there was no clear relationship between frequency of scraping and raw water quality or maintenance procedures. At the plants visited, operational convenience and tradition seemed to be the most important factors in establishing the frequency of scraping.

Cost of maintenance. The amount of sand removed in filter scraping operations was typically 1 in. (2.5 cm) (Table 3). One exception to this is Ilion, where, for unexplained reasons, 3–4 in. (7.5–10 cm) of sand was scraped from the filter bed. The removal of this amount of sand involves a labor requirement of 23–42 workhours/1000 sq ft (25–45 workhours/100 m^2). This is significantly greater than the labor requirement at the other plants, where the average was 5 workhours/1000 sq ft (100 m^2).

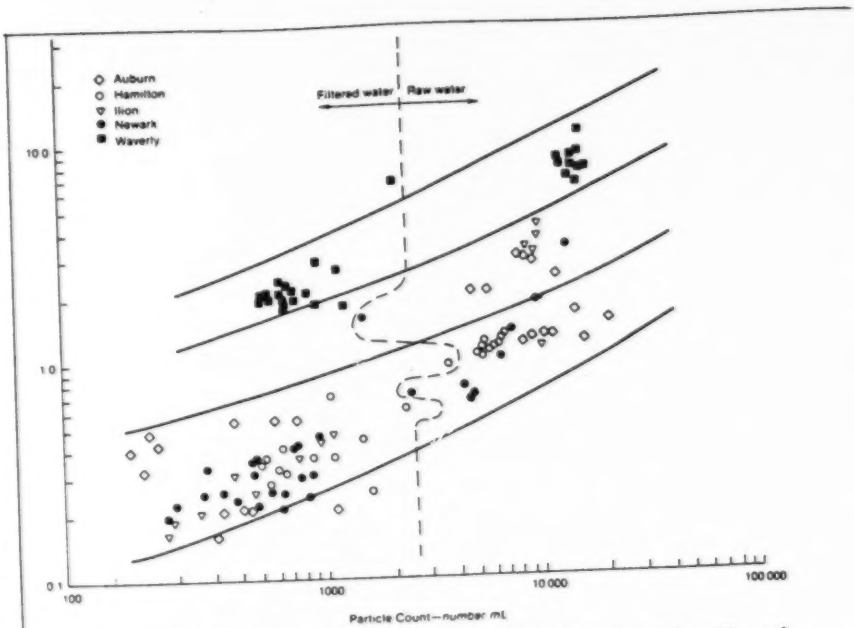

Figure 8. Turbidity versus particle count for Auburn, Hamilton, Ilion, Newark, and Waverly

At all of the plants, workers used broad shovels to remove the top layer of the filter bed. The most efficient scraping and sand removal operation was at Newark, where a motorized buggy was used to haul sand from the filter. Newark requires 2 workhours/1000 sq ft (100 m^2) of filter area for scraping. Other plants used wheelbarrows and hydraulic systems for moving sand into and out of the filter bed. An exception was Hamilton, where the sand was shoveled into 50-gal (190-L) drums, which were lifted from the bed by a backhoe. Shoveling sand into these drums is time-consuming and may account for the relatively high (8–9 workhours/1000 sq ft [9–10 workhours/100 m^2]) labor requirement at the Hamilton plant.

The estimated slow sand filter operation and maintenance costs for the plants are listed in Table 4. The labor for scraping was calculated by using the data from Table 3. The labor for resanding was calculated from information obtained at the plants. A resanding operation in which 6–12 in. (15–30 cm) of new or clean recycled sand are applied to a depleted bed requires 45–55 workhours/1000 sq ft (48–59 workhours/100 m^2). The day-to-day activities, such as sampling and adjusting valves, were assumed to require 1 workhour per day.

The frequency of resanding was calculated by using the scraping frequency, the average depth of sand removed per scraping operation, and the assumption that resanding will occur when the depth of sand in the filter bed has decreased by 1 ft (30 cm). For the removal of 1 in. (2.5 cm) of sand per scraping and a scraping frequency of 2 per year, the resanding frequency is 0.2 per year or once every six years.

The total labor costs were determined by using a $10/h wage rate. At Auburn, where summer student help is used, a wage rate of $3/h was assumed.

The added cost of replacing sand was calculated for the four plants that do not recycle sand by washing it. The sand replacement cost was based on a unit price of $12/ton. The plants that operate sand washing devices (Auburn, Ilion, and Ogdensburg) have no record of buying sand. Many US plants that practice sand washing and recycling have not had to purchase sand since the plant was first put into operation.[18]

The estimated total operation and maintenance cost per volume of water filtered ranges from $0.005/1000 gal ($0.013/10 m^3) of treated water at Auburn to $0.065/1000 gal ($0.17/10 m^3) at Hamilton. The average unit cost is $0.029/1000 gal ($0.075/10 m^3) of water treated. These results are consistent with previous findings[18] that most US slow sand filtration plants treat water for <$0.10/1000 gal (<$0.26/10 m^3).

Conclusions

In four of the ten scraping and resanding operations monitored during the study, there was some evidence of a ripening period. This evidence included filtrate turbidity or particle count, or both, that were greater for a filter that

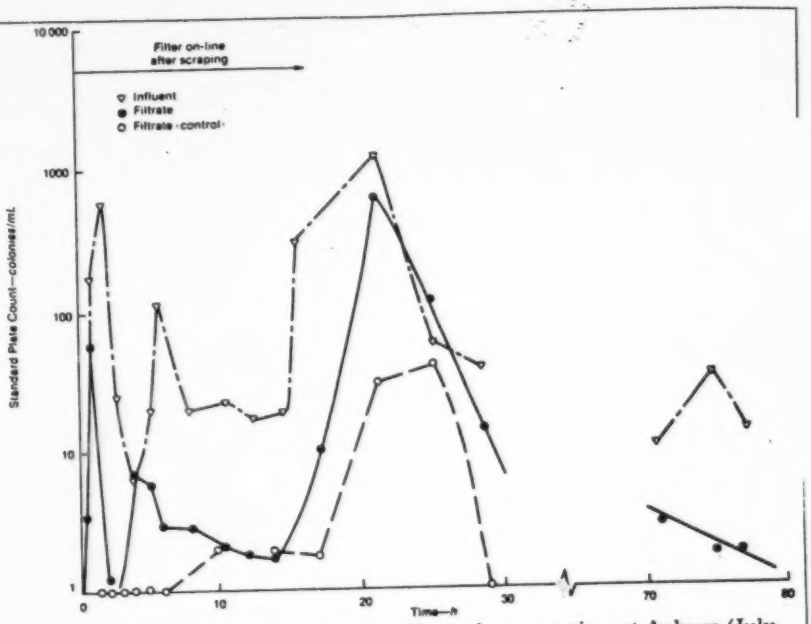

Figure 9. Density of standard plate count bacteria versus time at Auburn (July 1983; filter 1)

had been maintained than for a control filter that had been on-line for a significant period of time.

The lengths of the ripening periods ranged from 6 h to 2 weeks. The factor that seemed to have the most significant effect on filtrate quality was the amount and nature of the particulate matter in the raw water. The presence or absence of a ripening period did not seem to be related to the use of prechlorination, water temperature, scraping methodology, or frequency of filter maintenance.

The results suggest that a recently scraped filter is less efficient than a ripened control filter in attenuating a spike input of poorer quality raw water. This behavior was observed at several sites and was apparent in both the turbidity and particle count results.

Water production per filter run ranged from approximately 3000 gal/sq ft (123 m^3/m^2) to 16 000 gal/sq ft (656 m^3/m^2). The average frequency of filter scraping ranged from twice per year to 12 times per year. No clear relationship existed between the frequency of scraping and raw water quality or maintenance procedures. Operational convenience and tradition seemed to be the important factors. There is limited evidence that the filter run length was shorter during the summer.

Under typical conditions of filter scraping, i.e., removal of about 1 in. (2.5 cm) of dirty sand with shovels and conveyance of this sand from the filter with a motorized buggy or hydraulic transport, the labor requirement is approximately 5 workhours/1000 sq ft (100 m^2) of filter area. The resanding operation in which 6–12 in. (15–30 cm) of clean sand are applied to the depleted filter bed requires approximately 50 workhours/1000 sq ft (53 workhours/100 m^2). The average operation and maintenance cost for the plants visited during this study is \$0.029/1000 gal (\$0.075/10 m^3) of filtered water.

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